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The role of public policy in optimizing renewable energy development in the greater southern Appalachian mountains

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ABSTRACT

This research presents a third component of a comprehensive decision support system for energy planning that allows for combining existing electricity generating capabilities with increased use of renewable energy sources. It focuses on energy planning at the regional level, and concentrates specifically on the greater southern Appalachian mountains of the eastern United States: a region that was chosen for analysis not only due to its heavy dependence on coal for electricity, but also because of its potential for increased use of wind and solar power. Previous research used a geographic information system (GIS) model for identifying renewable energy potential to provide input data for a multi-objective linear programming (MOLP) model to determine the optimal constrained mix of renewable energy sources and existing fossil fuel facilities by balancing annual generation costs against the corresponding greenhouse gas emissions. This new component of the system analyzes three potential public policies—renewable portfolio standard, carbon tax, and renewable energy production tax credit—that have been used to foster increased renewable energy usage. These policies require minor modifications to the MOLP model for implementation. The results of these policy cases were then analyzed to determine the impact that these policies have on generation cost and pollution emissions within the region.

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1. Introduction

The costs associated with installing the technologies to exploit renewable energy sources have been on the decline in recent years, whereas the cost of fossil fuels has been following an overall increasing trend [1]. Although the combination of these trends has made the utilization of renewable energy sources increasingly more competitive, many areas with available renewable energy sources are not moving to take advantage of them in the near-future. In particular, many regions that are heavily dependent on fossil fuels for generation of electricity have been slower to integrate renewable energy sources into the existing infrastructure. This is true, for example, in the case of the greater southern Appalachian mountain region (Fig. 1), where 84.39% of the electricity generated is derived from coal. Although this amount includes coal that is co-fired with biomass, only 3.11% of the total electricity generation in the region is due to wind, hydro, and biomass combined (Table 1). In comparison, 48.2% of the electricity generated in the United States as a whole originates from coal [1].

With this heavy regional dependence on coal in mind, Arnette and Zobel [2] utilized a geographic information system (GIS) model to discover the availability of potential wind and solar farm sites within the greater southern Appalachian mountains. Incorporating appropriate geographic, atmospheric, and regulatory constraints on the utilization of these sources, the authors found that there were 203 possible wind farm sites and 477 potential solar farm locations in the region (Fig. 2). If all such sites were fully developed, an estimated 3.24% and 3.33% of baseline demand within the region could subsequently be met by wind and solar power, respectively [2]. By also including the potential for co-fire generation with biomass, Arnette and Zobel [2] showed that an estimated total amount of 16.92% of the current baseline generation could be

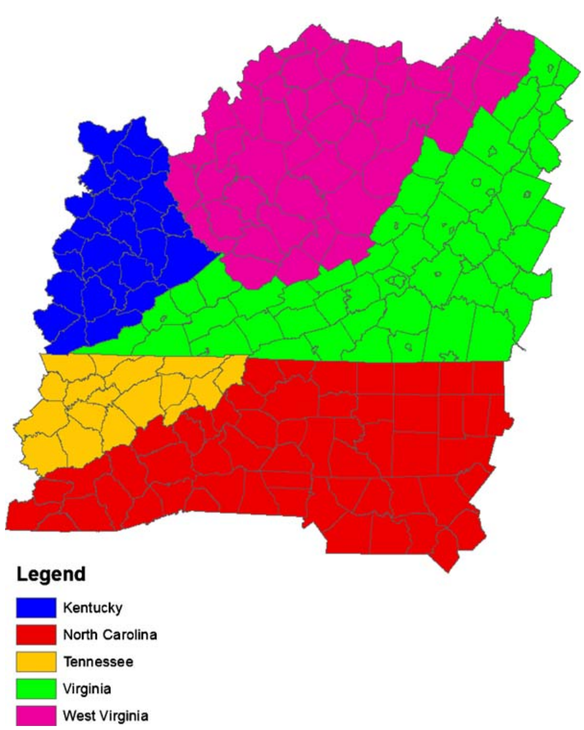

Fig. 1. Greater southern Appalachian mountain region.

Table 1
Electricity generation by source in the region.

Source	Number of facilities	MWh generated	Percentage of total generation
Coal	31	165,721,345	83.50%
Nuclear	1	17,619,492	8.88%
Gas	13	6,449,095	3.25%
Water	69	4,981,292	2.51%
Co-Fire	4	2,188,456	1.10%
Biomass	3	1,026,986	0.52%
Oil	22	241,841	0.12%
Wind	1	167,588	0.08%

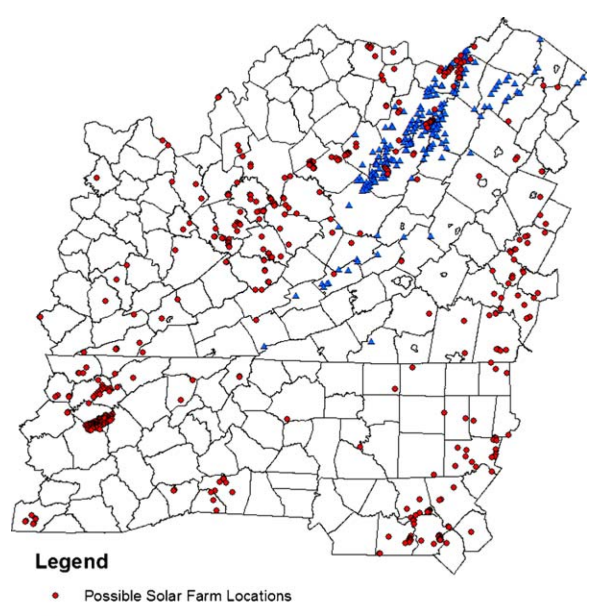

Fig. 2. Potential wind and solar farm sites within the region.

Table 2
Estimated cost of kWh generation by source.

Source	Average $/kWh	Reference
Biomass	$0.05200	[21]
Coal	$0.02000	[1]
Co-fire	$0.03000	[1,21]
Gas	$0.06993	[1]
Landfill	$0.05200	[1]
Nuclear	$0.02116	[1]
Oil	$0.03567	[1]
Water	$0.00967	[1]
Wind	$0.06993	[21]

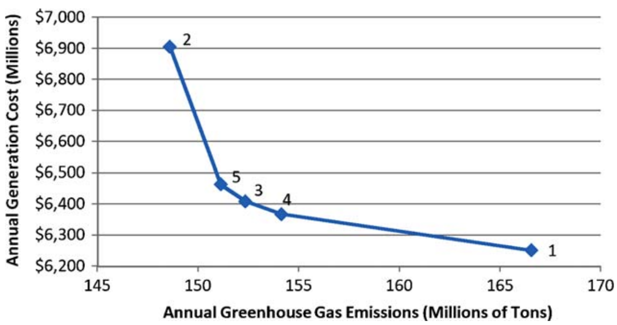

Fig. 3. Efficient frontier for optimization model scenarios in the original case.

met by fully utilizing the untapped potential of all three types of renewable energy.

The 203 possible wind farm sites within the region can produce electricity at an average cost of $0.1466/kWh, and the 477 potential solar farm sites can produce at an average of $0.2219/kWh. Though these averages are not competitive with the estimated cost of generation from other sources (Table 2), many of the potential sites are able to produce electricity at much lower actual costs. The cost effectiveness of co-fire as a short-term solution to reducing greenhouse gas emissions has been previously shown [3–5], yet implementation of this resource also has not been widespread because the increased cost associated with retrofitting coal plants for this co-fire capability does not increase actual capacity at these plants.

In order to better explore the tradeoffs inherent in increasing renewable energy investment, Arnette [6,7] extended the GIS model described in Arnette and Zobel [2] by proposing a multi-objective mixed-integer programming model for examining the relationship between these increased generation costs and the subsequent decrease in greenhouse gas emissions (see Appendix A). He provided an initial analysis of these tradeoffs by generating five different scenarios to illustrate the optimal results associated with differing priorities: (1) minimizing cost (without regard for emissions), (2) minimizing emissions (without regard for cost), (3) equal importance of cost and emissions, (4) relatively more preference for minimizing cost, and (5) relatively more preference for minimizing emissions. The results of these scenarios are given in Table 3, and the graph of the corresponding efficient frontier is shown in Fig. 3.

In scenario 2 (minimize emissions), the model indicated that the optimal (maximum) utilization of existing and new renewable energy sources was 14.20% of total generation. When cost was optimized in scenario 1, however, without considering emissions at all, then the resulting amount of renewable energy generation was only 5.73% of the total for the region. These results indicate that an opportunity exists to increase the amount of renewable generation through establishing appropriate public policy to help offset the emphasis on costs.

2. Method

This paper thus focuses on analyzing three different policies that previously have been utilized to encourage investment in renewable energy sources: renewable portfolio standards, a carbon tax, and tax credits for renewable generation. These policy alternatives are analyzed using the previously developed optimization model discussed above [6,7]. Each of these policies will require some modifications to the model, while the conceptual framework behind the model remains. Through the analysis of these three potential policies, it can be determined which policy, or mix of these potential policies, would most likely encourage development of renewable energy sources within the region.

Previous research papers have analyzed multiple renewable energy policies, such as those discussed above, utilizing simulation models [8,9]. Some of the previous mathematical programming models have included elements related to these ideas, such as the inclusion of a carbon tax [10], but have not analyzed these policies in relation to a baseline scenario or other policies. The three policies analyzed in this paper are not the only renewable energy policies that have been utilized previously, though they are among the most widely implemented. Additional policies such as cap-and-trade are not explored here but represent a potential future research direction.

We begin the discussion by introducing each of the three chosen policies, and by discussing how they may be incorporated into the existing multi-objective optimization model given in Appendix A.

2.1. Renewable portfolio standard (RPS)

A renewable portfolio standard is a government regulation stating that a certain percentage of electricity generation must be derived from renewable sources. Worldwide there have been a few nations that have implemented a RPS, such as the United Kingdom, Belgium, and Italy [11]. While there have been a few federal RPS bills proposed in the United States, however, none of them have been enacted at this point [12]. To date, RPS use in the U.S. has been based only on state regulations. There are currently 25 states that have a mandatory RPS in place. Each of these regulations differs with respect to the generation targets, the timeline, the sources considered as renewable, whether or not existing facilities are eligible, and other similar issues [13,14].

Currently, in the greater southern Appalachian mountain region only one state, North Carolina, has a mandatory RPS in place. The RPS for the state includes target values and timelines for different classes of producers: publicly owned (10% by 2018), and privately owned (12.5% by 2021). The state also includes a target value specifically for solar generation (0.2%). Virginia has enacted a non-binding RPS plan, specifying that 12% of generation by 2022 be derived from renewable sources. Each of these state plans includes variations that the other plan does not. For example, energy efficiency receives credit in NC, while wind and solar receive double credit in VA [14]. At this time, Kentucky, Tennessee, and West Virginia have not implemented RPS laws.

In relation to this research, a region-wide RPS can be implemented in the model by adding an additional constraint to the model given in Ref. [6,7] and summarized in Appendix A. This additional constraint requires that a minimum amount of generation be derived from renewable sources:

$$\sum_{i=1}^{N_i} M_i^w W_i H + \sum_{j=1}^{N_j} M_j^s S_j H + \sum_{y=1}^{Ny} M_p^{tc} B_{yp} F + \sum_{q=1}^{N_q} M_q^n (U_q^{ws} H + U_q^r) \geq Z \left(\sum_{i=1}^{N_i} M_i^w W_i + \sum_{j=1}^{N_j} M_j^s S_j + \sum_{p=1}^{N_p} M_p^c G_p + \sum_{q=1}^{N_q} M_p^n U_q \right) \quad (1)$$

Table 3
Results for the original case.

	Minimize cost	Minimize emissions	MiniMax–equal weight	MiniMax–cost weighted	MiniMax–emissions weighted
Total cost	$6,251,629,215	$6,905,758,165	$6,409,560,564	$6,368,243,366	$6,464,037,443
Total emissions (tons)	166,550,331	148,597,870	152,351,814	154,141,582	151,122,285
Capital investment utilization	45.13%	99.99%	46.51%	46.01%	58.75%
Renewable generation	5.73%	14.20%	12.70%	11.79%	13.16%

This requires the addition of two new parameters, and two new decision variables, as follows:

Z = the percentage of total generation derived from renewable sources (RPS)

H = credit multiplier for wind and solar generation

$$U_q^{ws} = \begin{cases} U_q, \text{ for all existing wind or solar facilities} \\ 0, \text{ otherwise} \end{cases}$$

$$U_q^{r} = \begin{cases} U_q, \text{ for all existing renewable facilities, except wind or solar} \\ 0, \text{ otherwise} \end{cases}$$

Eq. (1) thus compares the amount of energy generated from new wind and solar sites, biomass co-fire locations, and existing renewable sources, against that generated from all sources. The sum of the renewable generation must be equal or greater than the percentage of total generation defined in the RPS. The credit multiplier, H, is used to provided additional credit for wind and solar generation, such as the credit in place in the Virginia RPS, including existing wind or solar facilities. Therefore when H is greater than one, the sum of renewable generation on the left-hand side of the constraint is greater than the actual generation total. Increasing the value of H while holding the value of Z constant makes it easier to achieve the RPS but reduces the actual amount of renewable generation in the model.

2.2. Carbon tax

The second type of policy being considered is a carbon tax, or a tax placed on the emissions of CO_2. These taxes are placed on the generation of electricity from fossil fuel sources, such as coal, that emit CO_2 through the combustion process. CO_2 is the leading greenhouse gas emitted through electricity generation, and is recognized as one of the leading causes of climate change [15]. Carbon taxes are generally implemented to help increase the competitiveness of renewable energy sources in relation to traditional fossil fuel sources. The effects of carbon taxes on electricity generation have been studied previously [16,17], and are included in the cost minimization function used by the Regional Energy Deployment System (ReEDS) model developed by the National Renewable Energy Laboratory (NREL) [10].

The model developed in Appendix A, the original case, did not contain a carbon tax in cost calculations. This is due to the fact that a carbon tax has not been placed into law in the U.S. The implementation of a carbon tax is one that is largely unexplored in the United States, with the exception of a tax in place in Boulder, CO [18]. Though these taxes have been implemented in other countries, the amounts levied and the implementations of the tax have varied with respect to fuel sources and end-users, among other differences.

In this model, the carbon tax is implemented in one of the more basic, yet fairest, forms: a tax assessed directly on the emission of CO_2 at the source. This will require only a minor change to the cost minimization objective function formulated in Appendix A, while the rest of the model will remain unchanged. This new calculation includes a carbon tax placed on CO_2 emissions due to the use of fossil fuel sources such as coal, oil, and gas. This includes the use of coal and biomass in co-fire implementations. Though the current parameters of this model specify a 100% reduction in carbon emissions when replacing a ton of coal with a ton of biomass, if this value were to decrease then emissions from biomass would need to be taxed and this new equation can handle a change in this parameter. Thus the new cost objective function becomes:

$$\begin{aligned} Min \sum_{i=1}^{N_i} & W_i(C_i^{vw} + C^{kwm}K_i^w + C^{mwm}M_i^w) \\ & + \sum_{j=1}^{N_j} S_j(C_j^{vs} + C^{ksrm}K_j^s + C^{msm}M_j^s) \\ & + \sum_{p=1}^{N_p} \{(C_p^{vc} + C^{ac}G_pM_p^c + C^{tc}G_pT_p + C^{CO_2}E_p^{co-p}G_pT_p) \\ & + \sum_{y=1}^{N_y} (C^{tb}B_{yp} + C^{tbd}B_{yp}D_{yp} - C^{tc}B_{yp}F - C^{CO_2}E_p^{co-p}B_{yp}F \\ & + C^{CO_2}E_p^{co-b}B_{yp})\} + \sum_{q=1}^{N_q}(C_q^{mn}M_q^nU_q + C^{CO_2}E_q^{co-q}M_q^nU_q) \end{aligned} \quad (2)$$

where the new parameter C^{CO_2} is carbon tax, per ton of carbon dioxide emitted, is added to the function for all sources of generation except wind and solar.

2.3. Renewable energy production tax credit

Government sponsored tax credits to reduce the cost of generation from renewable sources have been used in the United States previously [19]. However, these incentives are currently set to expire in 2012, which is a shorter time-frame than required for development of the projects found in the previous results. Therefore, these tax credits were not implemented in the model formulated in Chapter 4. Through these tax credits, the production of electricity from renewable sources is made more competitive with existing fossil fuel sources. The renewable energy production tax credit (REPTC) attempts to achieve the same outcome as the carbon tax, increasing renewable energy usage through more competitive costs compared with fossil fuel sources. Though these two policies attempt to achieve the same thing, they do so through different means. The carbon tax penalizes fossil fuel usage, while the REPTC rewards investment in renewable energy technologies.

For implementation of this credit in the model, incentives will be placed into the annual generation cost objective function (Appendix A) to reduce the cost of generation for renewable energy sources. This credit will only be applied to wind and solar generation: other forms of renewable generation, such as hydro and biomass, are not eligible for this credit under current guidelines. In addition, this credit will be applied to any existing wind or solar facilities, as well as new installations credited in this model. This will reduce the overall generation costs within the region, while providing the incentive for more generation from renewable

sources. Thus the new cost objective function becomes:

$$\begin{aligned}Min\sum_{i=1}^{N_i} W_i(C_i^{vw} + C^{kwm}K_i^w + [C^{mwm} - D]M_i^w)\\ + \sum_{j=1}^{N_j} S_j(C_j^{vs} + C^{ksm}K_j^s + [C^{msm} - D]M_j^s)\\ + \sum_{p=1}^{N_p}\left\{(C_p^{vc} + C^{ac}G_pM_p^c + C^{tc}G_pT_p)\right.\\ \left. + \sum_{y=1}^{N_y}(C^{tb}B_{yp} + C^{tbd}B_{yp}D_{yp} - C^{tc}B_{yp}F)\right\} + \sum_{q=1}^{N_q} C_q^{mn}M_q^nU_q - DM_q^nU_q^{ws}\end{aligned} \tag{3}$$

This updated objective function requires a new parameter and a new set of decision variables:

D = renewable energy production credit per MWh generated from wind or solar

$$U_q^{ws} = \begin{cases} U_q & \text{for all existing wind or solar facilities} \\ 0 & \text{otherwise} \end{cases}$$

3. Calculation and analysis

The policies analyzed in this section are assumed to be implemented at the national level (or across all states within the region), as the region under study contains no state in its entirety and the implementation of a statewide policy would not affect the other states in the region. Though the implementation of a nationwide, or statewide, RPS would not require every area within a state to achieve the RPS goal, it is assumed that this region must be in line with the RPS. Therefore this policy analysis section is being used as a tool to provide insight into the impact that these possible policies would have on the selection of potential new renewable energy sources within this region. Additionally, although some generalizations can be made regarding these policies, the results of these policies would vary in other regions containing a different mix of existing sources and potential renewable sources.

3.1. Individual renewable energy policy analysis cases

The first subsection of policy analysis focuses on individually analyzing each of the three potential renewable energy policies outlined in the previous section. There are thus four cases in this subsection, as the RPS is analyzed in two different forms: one version calculates the actual renewable generation percentage while the second version applies double credit for generation from wind and solar. These four cases are analyzed with respect to the results of the model outlined previously in this chapter, which is referred to as the original case in the proceeding discussion.

3.1.1. Case 1: 15% RPS

The first policy chosen for analysis was a 15% renewable portfolio standard, with credit for renewable generation in place for wind, solar, hydroelectric, biomass-only facilities, as well as the biomass generation at co-fire plants. Though the latter source is generally not included in RPS calculations due to the majority of generation still relying on coal, the dependence on coal within this region makes the use of biomass co-fire much more important when attempting to increase renewable generation and decrease emissions of greenhouse gases. Additionally, non-co-fire renewable sources, such as hydroelectric and biomass, within the region currently account for only 3.37% of total baseline generation. The results of the GIS model provide 3.24% of baseline generation from potential wind farm sites and 3.33% of baseline generation from potential solar farm sites given the current constraints and parameters of the model. Thus a total of 9.94% of baseline generation could be generated from non-co-fire renewable energy sources in the current model. Installing the full capacity of potential wind and solar farms in the region is estimated to cost $46.16 billion, with an average cost of $0.1487/kWh of wind and $0.2219/kWh of solar. The total capital investment required for these installations could be prohibitive, thus the inclusion of a capital investment constraint in the linear programming model. In addition, the average cost per kWh of these installations is almost twice as much as the estimated highest cost per kWh for all sources in the model. Therefore achieving the maximum amount of non-co-fire generation would require a substantial increase in operating costs which is not desirable. Finally, if there is any expected growth in electricity demand within this region, the percentage of renewable generation will decrease in relation to this anticipated growth.

Given the parameters of the current model, the greatest percentage of renewable generation achieved in the original case was 14.20% in the minimized emissions scenario, while a minimum percentage of 5.73% was found in the minimized cost scenario. Each of the three MiniMax scenarios in the original case generated 11.79% or more of all electricity from renewable sources. Based on this result, along with the considerations outlined above, a value of 15% was chosen for the RPS in this first case. This value is greater than the mandatory RPS in place in North Carolina [14], and represents an aggressive policy to increase renewable generation. All generation is credited at actual value, so the value of H is one in this case and the use of the credit multiplier will be explored in the next case. Achieving the 14.20% renewable generation value in the original case required the use of 99.99% of the maximum $15 billion in capital investment, therefore the maximum capital investment must be increased to achieve renewable generation values of 15% or greater. In this case, the value of capital investment was increased to $25 billion, while all other parameters previously utilized are held constant.

The results of the 15% RPS with $25 billion in capital investment are displayed in Table 4. There are some new characteristics present in these results compared to the original results. The most interesting result found in this case is with regard to the use of capital investment. In the original case, the lowest use of capital investment was found in the minimized cost scenario and the greatest use was found in the minimized emissions scenario. In this case, the greatest use of capital investment still occurs in the minimized emissions scenario (99.99%), which results in the largest percentage of renewable generation (15.42%). However, the minimized cost scenario uses the second-highest amount of capital investment (85.15%), while the three MiniMax scenarios achieve lower greenhouse gas emissions while utilizing less capital investment (84.67%). Through the use of the RPS constraint, the way in which capital investment is utilized is more complex than in the original case.

With respect to the utilization of the different sources, there are a few points of interest. First, the utilization of biomass is 100% in all five scenarios while in the original case the use of biomass was 100% in only two of the scenarios and was 0% in one scenario. Though the use of biomass is 100% in all scenarios, the generation from biomass varies between 7.13% and 7.15% depending on the actual distribution of biomass between coal plants and the efficiency of the plants selected for co-fire. This result is not surprising as biomass co-fire is included in the achievement of the RPS and is the cheapest implementation of new renewable generation in this

Table 4
Results for case 1.

	Minimize cost	Minimize emissions	MiniMax–equal weight	MiniMax–cost weighted	MiniMax–emissions weighted
Total cost	$6,679,342,375	$7,203,300,471	$6,778,240,295	$6,742,634,514	$6,816,897,160
Total emissions (tons)	151,009,182	145,717,208	147,874,775	148,478,784	147,217,663
Capital investment utilization	85.15%	99.99%	84.67%	84.67%	84.67%
Renewable generation	15.00%	15.42%	15.00%	15.00%	15.00%

model. In addition, the utilization of coal plants varies between the five scenarios, with the lowest generation (71.78%) achieved in the minimize emissions scenario, and the greatest generation from coal is found in the minimize cost scenario (74.33%), again explaining the role of cost in energy planning and why this region has remained coal-dependent.

For the existing non-coal facilities, all biomass, co-fire, landfill, nuclear, water, and wind facilities are utilized at full capacity in all five scenarios, while the gas and oil facilities are subject to variation in utilization. The use of oil-based facilities varies, but the difference in total generation is less than 0.001% between the five scenarios. The use of gas facilities has a greater range of generation values, accounting for only 1.00% of total generation in the minimize cost scenario and 3.16% in the minimize emissions scenario. When focused solely on minimizing the cost function, gas is utilized at the lowest levels because the cost of gas is higher than the cost of other fossil fuel sources and some of the potential wind and solar sites. In the minimize emissions scenario, the use of coal is scaled back due to the emissions associated with this source, while the more expensive but less polluting gas plants are used at full capacity. The use of wind and solar sites is fairly constant in the five scenarios, except for the minimize emissions scenario where the use of wind and solar is maximized subject to the capital investment constraint.

The results of this case are similar to the results of the original case, with minor variation in the use of capital investment and the generation derived from these new renewable sites due to the implementation of the 15% RPS. The use of capital investment is around 85% in the four scenarios that achieve 15% exactly, thus showing the need for greater capital investment funds if an RPS is implemented with respect to this region.

The sensitivity of the 15% RPS value was analyzed to provide context for this choice of renewable generation requirement. A smaller RPS value, 12.5%, was utilized and the results were in line with the results found in this case. The increase in cost and decrease in emissions over the original case were smaller than when the RPS was set to 15%. A larger value for the RPS was not explored for this case due to the fact that installing every potential new wind and solar site, along with complete biomass utilization, only results in 17.09% renewable generation, and would require over $46.16 billion in capital investment.

In addition, the sensitivity of the capital investment constraint was explored as well. As the maximum capital investment is increased from $15 billion, the amount of renewable generation is increased, especially in the minimize emissions scenario wherein the cost is not considered, and results in additional reductions in emissions. However, the substantially larger generation costs associated with the wind and solar sites selected make these investments less desirable in the MiniMax scenarios as the impact on emissions is much less than the impact on cost. The MiniMax scenarios are considered preferable to the other two scenarios as only the MiniMax function utilizes both of the competing objectives and thus provide optimality as opposed to considering the objectives independent of one another. Achieving the 15% RPS requires a minimum of $22.2 billion in capital investment, and the use of more than $25 billion is not necessary as amounts greater than this amount are not utilized extensively, and increased capital investment increases annual generation costs more rapidly than the associated decrease in emissions, which is not a desirable outcome.

3.1.2. Case 2: 15% RPS with double credit

In the previous case achieving the 15% RPS required the use of more than the original capital investment constraint and was increased to $25 billion. However, Case 1 did not provide any additional credit for wind and solar generation, which is found in some RPS guidelines, such as the voluntary RPS in Virginia [14]. This second case provides double credit for wind and solar generation to achieve the 15% RPS, so the value of H in the constraint is set at 2. Through the use of double credit, 15% can be achieved given the original $15 billion capital investment constraint.

The results of this case (Table 5) are very interesting when compared to Case 1 due to the double credit for wind and solar installations. First, the only scenario to achieve the minimum amount of required renewable generation is the minimize cost scenario, while all other scenarios achieve a credited amount of renewable generation that is 15.80% or greater. To achieve the minimum amount of renewable generation requires the use of only 52.14% of the capital investment, and the amount of capital investment utilized increases as the credited renewable generation increases, but is never increased over 76% in the three MiniMax scenarios.

Though the use of double credit artificially inflates the percentage of renewable generation, the actual amount of renewable generation in four of the five scenarios greatly increases over the original case. The only scenario that does not have increased renewable generation is the minimize emissions scenario because the amount of renewable generation is maxed out given the capital investment constraint. Coinciding with increased renewable generation, these four scenarios also reduce emissions when compared to the original case. Therefore the use of this policy does what is intended—increase renewable generation without increasing costs of fossil fuel sources or providing government incentives.

Again, the sensitivity of the 15% RPS with double credit was analyzed utilizing the values of 12.5% and 17.5%. In the previous case, only 17.09% renewable generation could be achieved, but through the use of double credit for wind and solar, the 17.5% RPS value was

Table 5
Results for Case 2.

	Minimize cost	Minimize emissions	MiniMax–equal weight	MiniMax–cost weighted	MiniMax–emissions weighted
Total cost	$6,395,037,203	$6,885,482,722	$6,488,243,925	$6,453,442,572	$6,530,951,843
Total emissions (tons)	153,318,135	148,597,870	150,763,662	151,312,135	150,176,956
Capital investment utilization	52.14%	99.99%	65.63%	56.62%	75.99%
Credited renewable generation	15.00%	17.97%	16.27%	15.80%	16.79%
Actual renewable generation	12.40%	14.20%	13.32%	13.08%	13.59%

Table 6
Results for Case 3.

	Minimize cost	Minimize emissions	MiniMax–equal weight	MiniMax–cost weighted	MiniMax–emissions weighted
Total cost	$8,507,021,463	$8,972,039,034	$8,605,904,673	$8,572,991,322	$8,641,649,448
Total emissions (tons)	154,997,112	148,597,870	150,325,130	150,902,550	149,774,689
Capital investment utilization	46.01%	99.99%	73.38%	62.95%	83.31%
Renewable generation	11.35%	14.20%	13.53%	13.26%	13.76%

achievable. The results were in line with expectations based on the 15% RPS, with the lower RPS value achieving a smaller increase in cost and a smaller decrease in emissions and the larger RPS resulting in greater changes to the cost and emissions values on average.

3.1.3. Case 3: $14 carbon tax

Although the use of a carbon tax is present in the objective function in the ReEDS model [10], there is no value provided for this parameter. Therefore, the derivation of the carbon tax value used in this model is based on a review of marginal damage costs due to carbon emissions [20], wherein 103 estimates were analyzed. The median value of these studies was $14/ton, while the average value was $93/ton due to outliers in the distribution. Although the marginal damage cost of carbon is not the same as a carbon tax, this number provides a good estimate that can be used in this model. Furthermore, in the original case the minimize cost scenario provides the cheapest cost, but has the greatest amount of carbon emissions. For the other four scenarios, the average increase in cost versus one ton of carbon reduction is $17.68. However, the minimize emissions scenario decreases carbon emissions greatly but at a higher cost, $36.44 per ton of carbon, while in the three MiniMax scenarios the average is $11.43. Again, these carbon reduction costs are not the same as a carbon tax, but the numbers are in line with the $14 median value found in previous research, providing further validity for this value. The new cost function in Eq. (2) is utilized with the value of C^{CO_2} set to $14 and all other parameters are held constant.

The results of running the carbon tax scenario (Table 6) show that the renewable generation is greater in every scenario, except for minimize emissions, than in the original case. The renewable generation is already maximized in that scenario and cannot increase due to the capital investment constraint. Even though the level of renewable generation increases in the other scenarios, the cost is much greater than in previous cases due to the carbon-heavy nature of current generation within the region. The minimum cost achieved in this case is 36.08% greater than the minimum cost in the original case. This cost is also much greater than the minimum costs achieved in Case 1 and Case 2. The average increase in annual generation cost with this policy is 33.72%, while the average reduction in emissions is only 2.82%. Though the implementation of a carbon tax will impact the cost of generation in any region, the reliance on coal in this region means that the impact will be far greater in this region than in other areas of the United States. And given the amount of available renewable resources compared to the baseline generation from coal, the reduction in emissions is not as great as the increased cost.

The biggest source of carbon emissions in the region is due to generation from coal, and though the amount of generation from coal, and the associated emissions, decreases in comparison to the original case, the values are not as low as those obtained in Case 1 (15% RPS). However, the values in Case 1 were achieved by including an increase in capital investment availability. Therefore, the use of a $14 carbon tax reduces emissions by 6.94% over the original case in the minimize cost scenario, and this reduction comes at an increased cost of 36.08%. An unexpected result in this scenario is that biomass is not fully utilized, meaning that it is cheaper for some plants to pay the carbon tax than to implement co-fire when cost is the only consideration. In the minimize emissions scenario, the level of emissions cannot be reduced over the level achieved in the original case due to full utilization of capital investment. Therefore, the use of the carbon tax does reduce the amount of emissions in the region in four of the five scenarios, but if minimizing emissions is the main goal of the model one of the other policies can achieve the same results in emissions reduction at a much lower cost, and implementing no policy at all can achieve the same level of emissions by utilizing the results of the minimize emissions scenario in the original case.

Once again, a series of alternative values were used to analyze the sensitivity of the carbon tax value. Given the flexibility of the carbon tax price in comparison to the RPS values, a wider range of values were analyzed for sensitivity. Four additional values were selected for analysis, two values were smaller than $14/ton ($10 and $12) and two values were larger ($16 and $18). As the carbon tax is increased, the annual generation cost increases while the total tons of greenhouse gas emissions decreases.

The percentage change in cost for each scenario remained fairly constant across the five carbon tax values, with the greatest increase occurring in the minimize cost scenario and the smallest increase occurring in the minimize emissions scenario, and the three MiniMax scenario changes falling in between these extremes. Each increase in $2 in the carbon tax increased cost fairly evenly; there were no wild swings found across the carbon tax values. However, the change in emissions was proportionally smaller as the carbon tax was increased. This is due to the fact that the level of emissions does not decrease in the minimize emissions scenarios, as the values achieved in the original case cannot be improved upon without an increase in capital investment.

3.1.4. Case 4: $19 REPTC

Government incentives to encourage the use of renewable energy have taken many forms, most commonly through tax credits for investment or production. In the ReEDS model [10], a production tax credit of $19/MWh is utilized for wind, while an investment tax credit is used for concentrated solar power (CSP). The ReEDS model does not explore the use of solar PV, the solar technology utilized in this model. The production tax credit in ReEDS originally expired at the end of 2009, but has since been extended into 2012. In the original case, as given above, the use of this renewable energy production tax credit (REPTC) was not explored. Case 4 will thus implement the $19/MWh credit applied to both wind and solar. This case uses the new annual generation cost function specified in Eq. (3), with the value of D set to $19/MWh while all other parameters are held constant.

This case results in lower generation costs for all five scenarios (Table 7), which is to be expected. In addition, this reduction in annual generation cost makes some of the wind and solar sites more competitive than in the original case, resulting in more capital investment being utilized and increased renewable generation in all of the non-minimize emissions scenarios. Even with the increased use of renewable energy sources, the total emissions increase in two of the three MiniMax cases. This increase is due to the lower target cost found in the minimize cost scenario with the REPTC in place. This lower target value changes the relation-

Table 7
Results for Case 4.

	Minimize cost	Minimize emissions	MiniMax–equal weight	MiniMax–cost weighted	MiniMax–emissions weighted
Total cost	$6,154,163,497	$6,757,093,618	$6,309,997,573	$6,269,979,664	$6,356,670,672
Total emissions (tons)	166,550,331	148,597,870	152,360,626	154,190,843	151,042,730
Capital investment utilization	45.13%	99.99%	50.98%	46.45%	61.61%
Renewable generation	5.72%	14.20%	12.66%	11.76%	13.21%

ship between the deviations from both target values. Though the increase in emissions in these two scenarios is minimal (0.01% and 0.03%), this was an unexpected result.

As in the original case, the minimize cost scenario has no biomass utilization, and thus provides the highest percentage of generation from coal in this case. The use of biomass in the three MiniMax scenarios is lower than in the original case due to the lower cost for wind and solar due to the REPTC. Thus these sources become more cost-effective than the implementation of biomass co-fire at some coal plants. If the money is available for tax credit implementation within this region, the impact of this policy would result in lower costs but could actually increase emissions depending on the mix of generation sources selected.

Similar to the carbon tax, four additional values for the REPTC were analyzed to explore the sensitivity of this parameter. There was a nearly constant decrease in cost for each of the five values across the five optimization scenarios. As the REPTC value is increased from $15 to $23, the resulting change in annual generation cost remains similar, approximately 0.18% for each increase of $2. The percentage changes in emissions experienced less fluctuation than the cost changes. In the minimize emissions scenario the level of emissions achieved is constant and cannot be improved due to the capital investment constraint. In the minimize cost and three MiniMax scenarios, the values within each scenario only vary by less than 0.01% across the five different REPTC values, showing very little impact that this increased value has on emissions reduction.

3.2. Combined renewable energy policy analysis cases

The next four policy analysis cases use the previous policies and parameters in combination with one another. In the first two cases, the carbon tax will be used in conjunction with one of the two RPS cases, while the final two cases will look at the REPTC when utilized with the RPS cases. The utilization of a carbon tax and REPTC in one case is not analyzed as these policies attempt to achieve the same thing, increased cost-effectiveness of renewable energy, through different means and thus would be less effective when used together, especially given the much larger increases found through use of the carbon tax than the savings achieved when using the REPTC policy.

3.2.1. Case 5: $14 carbon tax/15% RPS

This case is the first of four cases to combine two of the previous standalone policies. The use of the $14 carbon tax outlined in Case 3 is combined with the 15% RPS outlined in Case 1, with single credit for wind and solar generation and the available amount capital investment raised to $25 billion.

The results (Table 8) are in line with the previous cases wherein these policies were implemented individually. The cost of generation is greatly increased, by an average of 37.64% over the five scenarios. Because of the RPS constraint this average increase is greater than the increase when utilizing a standalone carbon tax. The total tons of emissions are reduced by 4.40% on average, with the largest decrease corresponding to the minimize cost scenario. Even though carbon emissions are being taxed, the use of fossil fuels is still cheaper than some of the potential wind and solar sites as capital investment is not fully utilized in all non-minimize emissions scenarios. Biomass is fully utilized in all five scenarios, increasing in the minimize cost scenario when compared to the carbon-tax only case. The generation from coal is reduced over the original case, as well as the carbon tax-only case, and the amount of wind and solar is increased in all non-minimize emissions scenarios in comparison to the original case.

3.2.2. Case 6: $14 carbon tax/15% RPS with double credit

This case combines the carbon tax from Case 3 with the RPS specifications from Case 2, with results shown in Table 9. The use of the carbon tax increases the cost of generation by an average of 33.73%, while emissions are decreased in all non-minimize emissions scenarios by an average of 3.19%, which is less than in Case 5 due to the double credit. The use of the RPS does result in a slightly lower increase in average generation cost when compared to Case 3, but does not reduce emissions further.

The amount of renewable generation increases in three of the scenarios when compared to the standalone implementation of double credit RPS in Case 2 due to the increased cost of fossil fuel generation. In terms of capital investment utilization, the amount is held steady in four of the five scenarios when compared to Case

Table 8
Results for Case 5.

	Minimize cost	Minimize emissions	MiniMax–equal weight	MiniMax–cost weighted	MiniMax–emissions weighted
Total cost	$8,766,811,269	$9,225,224,528	$8,858,505,794	$8,831,212,570	$8,888,471,230
Total emissions (tons)	150,395,663	145,717,208	147,241,305	147,858,096	146,728,291
Capital investment utilization	85.01%	99.99%	84.49%	84.48%	85.86%
Renewable generation	15.00%	15.42%	15.00%	15.00%	15.02%

Table 9
Results for Case 6.

	Minimize cost	Minimize emissions	MiniMax–equal weight	MiniMax–cost weighted	MiniMax–emissions weighted
Total cost	$8,517,636,000	$8,947,627,119	$8,611,581,583	$8,580,442,746	$8,645,741,449
Total emissions (tons)	152,765,887	148,597,870	150,236,836	150,789,311	149,715,328
Capital investment utilization	47.37%	99.99%	75.08%	65.65%	84.61%
Credited renewable generation	15.00%	17.97%	16.74%	16.27%	17.20%
Actual renewable generation	12.53%	14.20%	13.56%	13.31%	13.79%

Table 10
Results for Case 7.

	Minimize cost	Minimize emissions	MiniMax–equal weight	MiniMax–cost weighted	MiniMax–emissions weighted
Total cost	$6,498,892,182	$7,007,391,086	$6,596,453,608	$6,561,248,174	$6,635,223,535
Total emissions (tons)	151,013,582	145,717,208	147,904,716	148,513,482	147,245,609
Capital investment utilization	85.32%	99.99%	84.67%	84.67%	84.67%
Renewable generation	15.00%	15.42%	15.00%	15.00%	15.00%

3, but is decreased in two scenarios and increased in one scenario when compared to Case 2. This decrease is the result of increased biomass utilization due to the carbon tax. In terms of generation in this case, the utilization of biomass is the same as in the previous carbon tax-only scenario. Again, the carbon tax and double credit for wind and solar still means that at some coal plants it is cheaper to pay the carbon tax than to implement biomass co-fire given the current parameters. Generation from coal, gas, wind, and solar is in line with previous results.

3.2.3. Case 7: $19 REPTC/15% RPS

This case explores the combined use of the REPTC outlined in Case 4 and the RPS specifications from Case 1. The results of this case are shown in Table 10. Lower costs are found in three of the scenarios when compared to the original case, even with the additional constraint placed on renewable generation. The only scenario which has an increased cost is the minimize cost scenario, but this increase is less than one percent and is due to the low level of renewable generation found in this scenario in the original case. Additionally, the total emissions decrease in all scenarios due to the increase in renewable generation to meet the RPS constraint.

Biomass is fully utilized in all of the scenarios and the generation from coal is decreased from the original case, but is in line with the previous cases using these policies. Gas utilization is at the lowest level in the minimize cost scenario due to the REPTC lowering the cost of wind and solar generation and the increased renewable generation required to meet the RPS constraint.

3.2.4. Case 8: $19 REPTC/15% RPS with double credit

The final case explores the use of the $19 REPTC (Case 4) and the 15% RPS with double credit (Case 2). The results of this combined policy are displayed in Table 11. The combination of these two policies results in lower generation costs and lower emissions compared to the original case, but the changes are not as large as those seen in Case 7, due to double credit for wind and solar generation.

The use of double credit for wind and solar combined with the REPTC for wind and solar results in an unusual pattern for capital investment utilization, with more capital investment being used in the minimize cost scenario than in the MiniMax–equal weight or MiniMax–cost weighted scenarios. In both the minimize cost and minimize emissions scenarios, while the utilization in the three MiniMax scenarios is lower.

4. Results

The analysis above considered three different base policies that have been utilized to increase renewable generation. One of these policies, the renewable portfolio standard, was analyzed in two variations, and several of the policies were then analyzed in different combinations. The only policies that were not analyzed in combination with one another were the carbon tax and the renewable generation production tax credit. These policies were not combined as they both try to achieve the same thing, making renewable sources more cost-effective by either increasing cost of fossil fuels or decreasing cost of wind and solar. Therefore, these two cost-altering policies were only combined with the RPS constraint and not used in conjunction with one another.

4.1. Minimizing cost vs. minimizing emissions

Of the two conflicting objectives, minimizing cost and minimizing emissions, only the cost function is altered through the use of the carbon tax and REPTC policies, which increase and decrease the minimum annual generation cost respectively. Though the RPS policy does not alter the cost function, this additional constraint placed on renewable generation does increase the minimum annual generation cost. As the emissions function is not altered in any of these cases, the minimum possible level of emissions (148.6 million tons) is never decreased over the original case when subject to the same parameters. The only cases where the minimum level of emissions is reduced are those with the increased availability of capital investment in the policies specifying 15% RPS with no double credit (Cases 1, 5, and 7). As a result, if decreasing emissions is considered the sole objective, then the use of any of these policies would not alter the mix of sources that result in the lowest possible level of emissions. Similarly, if cost was the only objective under consideration, then the RPS and carbon tax policies would always result in a higher cost, while the REPTC would always result in a lower cost. Thus the importance of analyzing both of these objectives in relation to one another can be observed from these results.

The efficient frontiers for the original case and for the eight policy cases analyzed are shown in Fig. 4. In the following sections, we discuss these results in more detail by focusing on the relative behavior exhibited within each of the three policy types: RPS, carbon tax, and REPTC.

4.2. RPS

The use of a stand-alone RPS is explored in two different versions (Fig. 5). The first version, represented in Case 1, implements a single-credit 15% RPS through an increase in capital investment from $15 billion to $25 billion. This case results in the largest average increase in cost (5.65%) for any non-carbon tax case. However, this scenario does result in the second best average decrease in emissions (4.09%). The second version of the RPS, Case 2, utilizes double credit for wind and solar generation in achieving the 15%

Table 11
Results for Case 8.

	Minimize cost	Minimize emissions	MiniMax–equal weight	MiniMax–cost weighted	MiniMax–emissions weighted
Total cost	$6,285,233,305	$6,736,818,175	$6,374,232,215	$6,343,423,783	$6,410,169,695
Total emissions (tons)	154,792,670	148,597,870	150,702,016	151,349,393	150,074,767
Capital investment utilization	67.70%	99.99%	67.56%	57.88%	79.08%
Credited renewable generation	15.00%	17.97%	16.36%	15.83%	16.92%
Actual renewable generation	11.99%	14.20%	13.36%	13.08%	13.64%

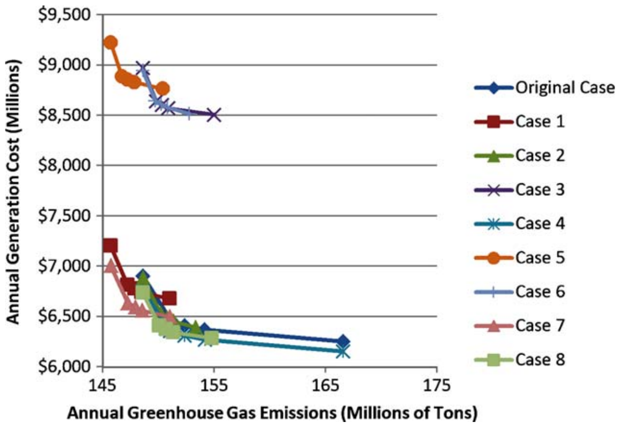

Fig. 4. Efficient frontiers for original case and policy cases. Optimization scenarios – (1) minimize emissions, (2) MiniMax–emissions weighted, (3) MiniMax–equal weight, (4) MiniMax–cost weighted, (5) minimize cost.

RPS and does not require additional capital investment over the original case. This case results in a smaller average increase in annual generation cost (1.12%) and a smaller average decrease in emissions (2.86%), though the ratio of cost increase to emissions decrease is better for this case. Therefore, the use of the 15% RPS with double credit for wind and solar would be the most economically efficient way to decrease emissions, especially if additional funds were not available to increase capital investment or implement a REPTC. This case provides a cost-effective way to decrease emissions over the original case without requiring the government to provide tax credits or requiring energy companies to secure more sources of funding.

If an increase in capital investment is made available, then this will result in increased renewable generation and decreased emissions. But this increase is only cost-effective up to a certain point in this region, as some of the potential wind and solar sites are not cost-effective, reducing emissions by a much smaller percentage than the associated increase in cost from using these more expensive sites. Most of these sites are less cost-effective due to their size, with the fixed costs being spread over less generation.

4.3. Carbon tax

The use of the carbon tax in Cases 3, 5, and 6 results in large increases in annual generation cost for each scenario (Fig. 6). Given that the greater southern Appalachian region is so heavily dependent on fossil fuel sources, particularly coal, the implementation of a carbon tax could be economically crippling to the region unless

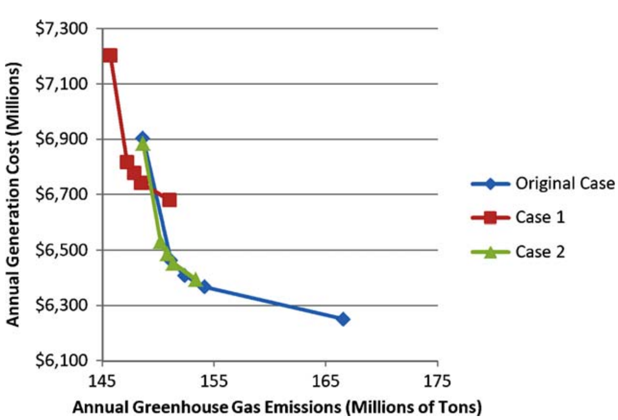

Fig. 5. Efficient frontiers for RPS-only cases.

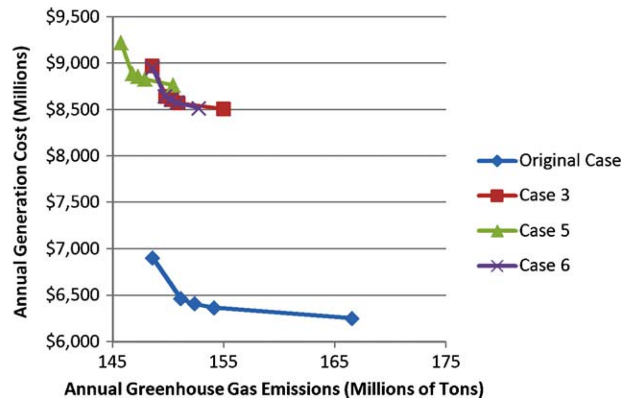

Fig. 6. Efficient frontiers for carbon tax cases.

these increased tax revenues were being offset with cuts to tax revenue from other sources. Even though the use of the carbon tax in combination with an RPS constraint (Case 5) does result in the largest decreases in total emissions, there are other scenarios that reduce emissions nearly as much without having such a large impact on cost. The other reason that a carbon tax would be unadvisable within this region is the small percentage of electricity that can be generated from renewable sources in relation to the dominance of carbon-based sources. Given the current constraints of the GIS model, only 3.24% and 3.33% of baseline demand within the region could be met by wind and solar respectively. However, many of the potential wind and solar sites have associated generation costs that are as high as $0.49/kWh of wind and $0.64/kWh of solar, which is extremely expensive and uncompetitive. Therefore, only a small percentage of generation can be effectively replaced with new wind and solar resources. Even in the cases that utilize the carbon tax, the minimum amount of coal generation possible is 71.78% and that comes through the increased availability of capital investment. Therefore, unless a greater percentage of coal generation can be replaced with renewable sources, whether through relaxing the constraints of the GIS model or through the exploration of distributed generation with small-scale installations, the use of a carbon tax has less benefit than the other policies. The three carbon tax cases do not provide substantially greater reductions in emissions than the other policy cases, but result in much higher generation costs due to the dependence on coal as the primary source of generation in the region.

4.4. REPTC

The use of the REPTC results in lower costs when utilizing the same amount of capital investment as in the base case (Cases 4 and 8), while in the case where capital investment is increased to meet the RPS requirement (Case 7) the cost increases in one scenario while decreasing in three of the other scenarios (Fig. 7). The use of the REPTC as a standalone policy (Case 4) does result in lower emissions for two of the five scenarios, while increasing emissions in two of the others. However, these increases and decreases are the smallest changes experienced across all eight cases. Therefore, the use of the REPTC as a standalone policy would not be recommended, as the policy can achieve a greater impact when combined with an RPS (Cases 7 and 8). Case 7 relies on more capital investment availability, which may not be feasible at this time. However, this increase in capital investment does decrease costs slightly in three of the scenarios and results in the third best average decrease in emissions over the MiniMax scenarios. Case 8, which does not rely on more capital investment, has the second greatest decrease in average annual generation cost along with a modest reduction in

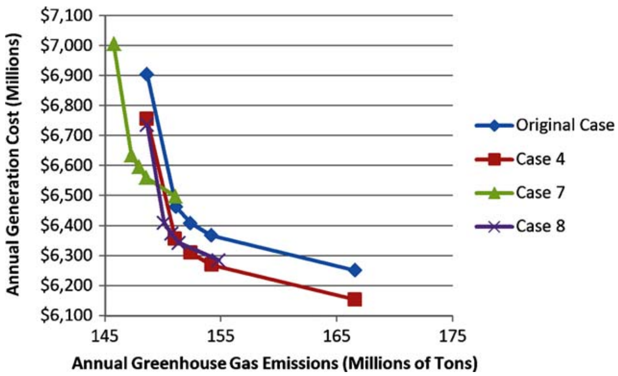

Fig. 7. Efficient frontiers for REPTC cases.

emissions. The use of the REPTC represents the opposite approach to a carbon tax, decreasing the cost of renewable generation, and therefore requires the tax credits made available to be offset with budget cuts or tax increases in other areas. If the availability of REPTC funds is there, then Case 8, which utilizes a 15% RPS with double credit for wind and solar, would be the most effective use of these funds.

5. Conclusions

The model utilized in this research is composed of two competing objectives: the minimization of annual generation costs and the minimization of annual greenhouse gas emissions. As seen in the results of the original model and the eight policy cases above, the target values achieved when solving for one of the objectives independently of the other are in opposition with one another. It is not possible to achieve both the minimum cost and minimum emissions with the same mix of energy sources. Through the use of the MiniMax function, the model can be solved in a manner that considers both of the objectives. However, there are an infinite number of solutions that lie on the efficient frontier between the two target values. Through the use of weighting, a preference can be expressed for one objective in relation to the other objective, and a solution on the efficient frontier is then identified for that weighting scenario. There were three MiniMax weighting scenarios utilized in this research, one in which the objectives were equally weighted, one in which the emissions objective was twice as important as the cost objective, and a scenario in which the cost objective was twice as important as the emissions objective. Determining the weights for the objective functions is a subjective process, and these three scenarios analyzed in this research represent only a fraction of the possible weighting schemes.

If one wanted to focus specifically on one of the five weighting scenarios, the MiniMax–cost weighted would be the best choice due to two reasons. First, the decision to invest in new technologies and energy infrastructure is often very dependent on the costs involved and this is the only scenario in which the cost objective was considered more important than the emissions objective, while still considering the emissions function. The policy cases all involve some degree of government involvement, and it is reasonable to assume that minimizing cost would be of upmost importance to users of this system. The second reason is that the target value for the cost function ($6,251,629,215) in the original case is a magnitude of more than 40 times greater than the target value for the emissions objective (148,597,870). As the cost function will also produce values much greater than the emissions function, any percentage deviation for the cost function represents a larger absolute increase over the target cost than absolute change for the same deviation in the emissions function.

The results of this policy analysis section provide some insight into potential government legislation to increase renewable generation. These results should not be extrapolated to the entire country or other regions due to the intensely carbon-based generation within this region. As a result of the dependence on coal in the region, the use of a carbon tax is the least advisable of the policies considered and can result in cost increases of 30% or more. If government funds are available for tax credits, then the use of these credits in conjunction with an RPS, especially one in which double credit is provided for wind and solar generation, can provide better results than the use of these tax credits on their own. Finally, of the policies considered, the use of an RPS is the most cost effective way to cut down on emissions while moderately impacting the generation costs. If a government policy were implemented in this region, this would be the most advisable choice given the current availability of wind and solar resources and the dependence on fossil fuels, particularly coal.

Appendix A. Model formulation

A.1. Decision variables

$$W_i = \begin{cases} 1 & \text{if a wind farm is to be placed at location } i \text{ for } i = 1, \ldots, N_i \\ 0 & \text{otherwise} \end{cases}.$$

where N_i = the number of possible wind farm locations.

$$S_j = \begin{cases} 1 & \text{if a solar farm is to be placed at location } j \text{ for } j = 1, \ldots, N_j \\ 0 & \text{otherwise} \end{cases}.$$

where N_s = the number of possible solar farm locations, B_{yp} = tons of biomass transported between county y and coal plant p, for y = 1,. . ., N_y where N_y = the number of counties in the region and p = 1,. . ., N_p where N_p = the number of coal plants in the region.U_q = capacity utilization of existing non-coal electricity generation facility q relative to baseline levels, for q = 1,. . ., N_q where N_q = the number of existing non-coal facilities in the region.G_p = capacity utilization of existing coal electricity generation facility p relative to baseline levels, for p = 1,. . ., N_p where N_p = the number of existing coal plants in the region

$$G_p, U_q \leq 1$$

$$B_{yp}, G_p, U_q \geq 0$$

A.2. Parameters

A.2.1. Wind farms

C_i^{vw} is annualized capital investment of wind farm location i
C^{kwm} is annual operating and maintenance costs per installed kW of wind capacity
K_i^w is kW capacity at wind farm location i
C^{mwm} is annual operating and maintenance costs per MWh of wind generation
M_i^w is expected annual MWh generation at wind farm
C^{kw} is cost of installing one kW of wind capacity
C^{af} is cost of clearing one acre of forest land for wind farm installation
A_i^f is acres of forested land at wind farm location i
C^l is cost per degree of slope at wind farm location
L_i is average degree of slope at wind farm location i

A.2.2. Solar farms

C_j^{vw} is annualized capital investment of solar farm location j
C^{ksm} is annual operating and maintenance costs per installed kW of solar capacity
K_j^s is kW capacity at solar farm location j

C^{msm} is annual operating and maintenance costs per MWh of solar generation
M_j^s is expected annual MWh generation at solar farm j
C^{ks} is cost of installing one kW of solar capacity

A.2.3. Coal or co-fire plants

C_p^{vc} is annualized capital investment for co-fire retrofit at coal plant p
C^{tc} is cost per ton of coal
C^{tb} is cost per ton of biomass
C^{tbd} is cost of transporting one ton of biomass one mile
D_{yp} is estimated distance between county y and coal plant p
$C^{ac}$is additional cost per MWh generated at a coal plant, including labor, operating, etc.
M_p^c is MWh generated at coal plant p in baseline year
T_p is tons of coal used at coal plant p in baseline year
F is percentage efficiency of one ton of biomass versus one ton of coal, assumed constant for all plants in the region
B_y^{avail} is tons of biomass available within county y
X is percentage of total fuel generating tons that can be derived from biomass
C^{kb} is cost of retrofitting a coal-fired plant for biomass co-fire per kW of capacity
K_p^c is overall kW capacity at coal plant p
M_p^{tc} is MWh generated per ton of coal in baseline year at plant p

A.2.4. Existing non-coal facilities

C_q^{mn} is cost per MWh generated at non-coal facility q
M_q^n is MWh generated at non-coal facility q in baseline year

A.2.5. Emissions

E_p^{co-p} is tons of CO_2 emissions per ton of coal used at plant p
E_p^{so-p} is tons of SO_2 emissions per ton of coal used at plant p
E_p^{no-p} is tons of NO_x emissions per ton of coal used at plant p
E_p^{co-b} is tons of CO_2 emissions per ton of biomass used at plant p
E_p^{so-b} is tons of SO_2 emissions per ton of biomass used at plant p
E_p^{no-b} is tons of NO_x emissions per ton of biomass used at plant p
E_q^{co-q} is tons of CO_2 emissions per MWh generated at non-coal facility q
E_q^{so-q} is tons of SO_2 emissions per MWh generated at non-coal facility q
E_q^{no-q} is tons of NO_x emissions per MWh generated at non-coal facility q

A.2.6. Overall

M^{bass} is electricity generation (MWh) within region in baseline year
H is growth factor
V is total amount of capital investment available

Objective function 1 (annual electricity generation costs):

$$
\begin{aligned}
& Min\sum_{i=1}^{N_i} W_i(C_i^{vw} + C^{kwm}K_i^w + C^{mwm}K_i^w) + \sum_{j=1}^{N_j} S_j(C_j^{vs} + C^{ksm}K_j^s + C^{msm}M_j^s) \\
& + \sum_{p=1}^{N_p} \left\{ (C_p^{vc} + C^{ac}G_pM_p^c + C^{tc}G_pT_p) \right. \\
& \left. + \sum_{y=1}^{N_y} (C^{tb}B_{yp} + C^{tbd}B_{yp}D_{yp} - C^{tc}B_{yp}F) \right\} + \sum_{q=1}^{N_q} C_q^{mn}M_q^nU_q
\end{aligned}
$$

Objective function 2 (total greenhouse gas emissions):

$$
\begin{aligned}
& Min\sum_{p=1}^{N_p} \left\{ ([E_p^{co-p} + E_p^{so-p} + E_p^{no-p}]G_pT_p) \right. \\
& \left. - \sum_{y=1}^{N_y} ([E_p^{co-p} + E_p^{so-p} + E_p^{no-p}]B_{yp}F + [E_p^{co-b} + E_p^{so-b} + E_p^{no-b}]B_{yp}) \right\} \\
& + \sum_{q=1}^{N_q} [E_q^{co-q} + E_q^{so-q} + E_q^{no-q}]M_n^qU_q
\end{aligned}
$$

A.3. Constraints

Biomass utilization within each county

$$\sum_{p=1}^{N_p} B_{yp} \le B_y^{avail}$$

Maximum amount of biomass that can be co-fired at each coal plant

$$\sum_{y=1}^{N_y} B_{yp}F \le G_pT_pX$$

Electricity generation

$$\sum_{i=1}^{N_i} M_i^wW_i + \sum_{j=1}^{N_i} M_j^sS_j + \sum_{p=1}^{N_p} M_p^cG_p + \sum_{q=1}^{N_q} M_q^nU_q \ge M^{base}(1+H)$$

Capital investment

$$
\begin{aligned}
& \sum_{i=1}^{N_i} K_i^w(C^{kw} + C^{af}A_i^f + C^lL_i) + \sum_{j=1}^{N_j} C^{ks}K_j^s \\
& + \sum_{p=1}^{N_p} \left[C^{kb}\left(\frac{K_p^c}{M_p^c}\right) M_p^{tc} \sum_{y=1}^{N_y} B_{yp}F \right] \le V
\end{aligned}
$$

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